

MOLECULAR HYDROGEN ABSORPTION FROM THE HALO OF A $Z \sim 0.4$ GALAXY

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ABSTRACT

Lyman- and Werner-band absorption of molecular hydrogen (H_2) is detected in $\sim 50\%$ of low-redshift ($z < 1$) DLAs/sub-DLAs with $N(H_2) > 10^{14.4} \text{ cm}^{-2}$. However, the true origin(s) of the H_2 -bearing gas remain elusive. Here we report a new detection of an H_2 absorber at $z_{\text{abs}} = 0.4298$ in the *HST*/COS spectra of quasar PKS 2128–123. The total $N(HI)$ of $10^{19.50 \pm 0.15} \text{ cm}^{-2}$ classifies the absorber as a sub-DLA. H_2 absorption is detected up to the $J = 3$ rotational level with a total $\log N(H_2) = 16.36 \pm 0.08$ corresponding to a molecular fraction of $\log f_{H_2} = -2.84 \pm 0.17$. The excitation temperature of $T_{\text{ex}} = 206 \pm 6 \text{ K}$ indicates the presence of cold gas. Using detailed ionization modeling we obtain a near-solar metallicity (i.e., $[O/H] = -0.26 \pm 0.19$) and a dust-to-gas ratio of $\log \kappa \sim -0.45$ for the H_2 -absorbing gas. The host galaxy of the sub-DLA is detected at an impact parameter of $\rho \sim 48 \text{ kpc}$ with an inclination angle of $i \sim 48^\circ$ and an azimuthal angle of $\Phi \sim 15^\circ$ with respect to the QSO sightline. We show that co-rotating gas in an extended disk cannot explain the observed kinematics of Mg II absorption. Moreover, the inferred high metallicity is not consistent with the scenario of gas accretion. An outflow from the central region of the host galaxy, on the other hand, would require a large opening angle (i.e., $2\theta > 150^\circ$), much larger than the observed outflow opening angles in Seyfert galaxies, in order to intercept the QSO sightline. We thus favor a scenario in which the H_2 -bearing gas is stemming from a dwarf-satellite galaxy, presumably via tidal and/or ram pressure stripping. Detection of a dwarf galaxy candidate in the *HST*/WFPC2 image at an impact parameter of $\sim 12 \text{ kpc}$ reinforces such an idea.

Subject headings: galaxies:haloes – galaxies:ISM – quasars:absorption lines – quasar:individual (PKS 2128–123)

1. INTRODUCTION

Molecular hydrogen (H_2) is the most abundant molecule in the universe, and it plays a crucial role in star formation in the interstellar medium (ISM; see Shull & Beckwith 1982, for a review). H_2 exhibits numerous transitions from its ground electronic state to the Lyman and Werner bands at ultraviolet (UV) wavelengths (900–1130 Å). The Lyman- and Werner-band absorption of H_2 is detected in diverse astronomical environments, e.g., in the Galactic disk (Spitzer & Jenkins 1975; Savage et al. 1977), Galactic halo (Gillmon et al. 2006; Wakker 2006), Magellanic Clouds (Tumlinson et al. 2002; Welty et al. 2012), Magellanic Stream (MS; Sembach et al. 2001), Magellanic Bridge (MB; Lehner 2002), high-velocity clouds (HVCs; Richter et al. 1999, 2001), intermediate-velocity clouds (IVCs; Gringel et al. 2000; Richter et al. 2003), and in high-redshift damped Ly α absorbers (DLAs; Ledoux et al. 2003; Noterdaeme et al. 2008).

For high-redshift ($z > 1.8$) absorbers, the UV transitions of H_2 get redshifted to optical wavelengths. Absorption lines of high- z H_2 absorbers, thus, are well studied using high-resolution optical spectra obtained from ground-based telescopes (e.g., Srianand et al. 2005, 2008, 2012). Due to the lack of high-resolution, UV-sensitive, space-based spectrograph, H_2 was never studied in absorption at low- z ($z < 1$) beyond the Local Group until the last decade. However, the high throughput of the Cosmic Origins Spectrograph (COS) on board the *Hubble Space Telescope* (*HST*) has recently enabled such observation. Detection and analysis of low- z H_2 absorbers have been presented in several recent studies (i.e.,

Crighton et al. 2013; Oliveira et al. 2014; Srianand et al. 2014; Dutta et al. 2015; Muzahid et al. 2015b).

Using archival *HST*/COS spectra, Muzahid et al. (2015b) have surveyed H_2 absorption in 27 low- z DLAs/sub-DLAs for the first time and have reported detections of 10 H_2 absorbers in total. The H_2 detection rate at low- z , i.e. $50^{+25}_{-12}\%$, for systems with $N(H_2) > 10^{14.4} \text{ cm}^{-2}$, is a factor of $\gtrsim 2$ higher than that found at high- z by Noterdaeme et al. (2008). The increase of the cosmic mean metallicity of DLAs/sub-DLAs (e.g., Rafelski et al. 2012; Som et al. 2013) and the dimming of the ambient radiation field due to the decrease of the cosmic star formation rate density with cosmic time (e.g., Bouwens et al. 2011; Haardt & Madau 2012) are thought to be responsible for such an enhanced H_2 detection rate at low- z .

The median $N(HI)$ value of $10^{19.5} \text{ cm}^{-2}$ for the low- z sample of Muzahid et al. (2015b) is an order of magnitude lower than that of the high- z sample. Nevertheless, the low- z H_2 absorbers show molecular fractions, $f_{H_2} = 2N(H_2)/[N(HI) + 2N(H_2)]$, that are comparable to the high- z H_2 absorbers (e.g., median $\log f_{H_2} = -1.93 \pm 0.63$). High molecular fractions at lower $N(HI)$ values indicate that (a) the density is extremely high and/or (b) the prevailing radiation field is very weak in the absorbing gas.

Using simple photoionization models and from the lack of high J (i.e., $J > 3$) excitations, Muzahid et al. (2015b) have inferred that the radiation field is much weaker than that seen in the Milky Way diffuse ISM (Black et al. 1987), in contrast to high- z H_2 absorbers (e.g., Srianand et al. 2005). The density of the H_2 -absorbing gas is predicted to be in the range of $10\text{--}100 \text{ cm}^{-3}$ (or lower), which is consistent with that of the

Galactic diffuse ISM. The median rotational excitation temperature of $T_{01} = 133 \pm 55$ K¹ is also suggestive of a diffuse atomic gas-phase (Snow & McCall 2006).

Detecting host galaxies of high- z H₂ absorbers is difficult, and searches have not been successful so far. The advantage of studying low- z H₂ absorbers is that it is relatively easier to identify the host galaxies responsible for absorption. For example, 8 of the 10 H₂ absorbers in the sample of Muzahid et al. (2015b) have host galaxies identified from the literature. Interestingly, 5 of the 8 H₂ absorbers have host galaxies at an impact parameter of $\rho > 20$ kpc. Moreover, the two systems with the highest molecular fractions show the largest impact parameters (i.e. $\rho > 50$ kpc; see Fig. 9 of Muzahid et al. 2015b). Even for the lowest impact parameter ($\rho < 10$) system the QSO sightline is well beyond the stellar disk of the host galaxy (see, e.g., Petitjean et al. 1996; Chen et al. 2005). It is, therefore, conjectured that the low- z H₂ absorbers are not related to star-forming disks, but emerge from tidally stripped or ejected disk material in the halo.

Here we present a detailed analysis of a new H₂ absorber in a sub-DLA at $z_{\text{abs}} = 0.4298$ detected toward QSO PKS 2128–123. The host galaxy of the H₂ absorber is detected at $\rho \sim 48$ kpc. The main focus of this work is to understand the origin of the detected H₂ absorption. The article is organized as follows: In Section 2 we present the available observations. Analysis related to absorption spectra and ionization models are presented in Section 3. In Section 4 analysis of the host galaxy is presented. Our results are discussed in Section 5 followed by a summary in Section 6. Throughout this paper we adopt an $H_0 = 70$ km s^{−1} Mpc^{−1}, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$ cosmology. Solar abundances of heavy elements are taken from Asplund et al. (2009). All the distances given are proper (physical) distances.

2. OBSERVATIONS

2.1. Absorption Data

2.1.1. *HST*/COS

Far-ultraviolet (FUV) spectra of the background QSO PKS 2128–123 were obtained using *HST*/COS Cycle-21 observations under program ID GO-13398 as a part of our “Multiphase Galaxy Halos” survey. The properties of COS and its in-flight operations are discussed by Osterman et al. (2011) and Green et al. (2012). The observations consist of G130M and G160M FUV grating integrations at a medium resolution of $R \sim 20,000$ (FWHM ~ 18 km s^{−1}) over the wavelength range of 1140–1800 Å. However, due to the complete Lyman-limit break from the absorber of interest at $z_{\text{abs}} = 0.4298$, no QSO flux is recorded for $\lambda < 1310$ Å. The data were retrieved from the *HST* archive and reduced using the STScI CALCOS v2.21 pipeline software. The reduced data were flux calibrated. To increase the spectral signal-to-noise ratio (S/N), individual exposures were aligned and co-added using the IDL code “*coadd_x1d*” developed by Danforth et al. (2010)². The combined spectrum has a S/N ~ 9 –20 per resolution element. As the COS FUV spectra are significantly oversampled (i.e. 6 raw pixels per resolution element), we binned the data by 3 pixels. This improves the S/N per pixel by a factor of

$\sqrt{3}$. All our measurements and analyses were performed on the binned data.

In addition to the FUV observations, near-UV (NUV) spectral data are also available for the QSO. These NUV observations consist of G185M and G225M grating integrations. The G185M grating data were obtained using *HST*/COS Cycle-19 observations under program ID GO-12536, whereas the G225M grating data were obtained by our own program, ID GO-13398. Individual G185M and G225M integrations were co-added using custom-written IDL code following similar algorithms to the “*coadd_x1d*”. Both G185M and G225 data consist of three 35 Å stripes separated by two 65 Å gaps. G185M data cover 1670–1705 Å, 1770–1805 Å, and 1870–1905 Å, whereas G225M data cover 2100–2135 Å, 2200–2235 Å, and 2300–2335 Å. The co-added G185M spectrum has an S/N of 5–13 per resolution element. However, the G225M spectrum has an S/N < 3 per resolution element.

2.1.2. *Keck*/HIRES

The optical spectrum of PKS 2128–123 was obtained with the HIRES mounted on the Keck-I 10 m telescope on Mauna Kea in Hawaii. The QSO was observed under program IDs C54H (PI: W. Sargent), U51H (PI: S. Vogt), and C99H (C. Steidel). We use the spectrum obtained from the Keck Observatory Archive’s automated reduction pipeline software for our analysis. The pipeline-reduced spectrum was not flux calibrated; however, the wavelength was both vacuum and heliocentric velocity corrected. The final reduced spectrum covered 3200–6100 Å at a spectral resolution of $R \sim 45,000$ (FWHM ~ 6.6 km s^{−1}) with a spectral S/N of ~ 20 and ~ 45 per pixel in the blue and red parts, respectively. We note that the pipeline-reduced spectrum used here is identical to the one independently reduced and kindly provided to us by Hadi Rahmani using MAKEE³ data reduction software. Continuum normalizations of all the spectra (COS/FUV, NUV and Keck/HIRES) were done by fitting the line-free regions with smooth low-order polynomials.

2.2. Galaxy Data

A 600 s *HST*/WFPC2 F702W image of the PKS 2128–123 field was obtained under program ID 5143. The reduced and calibrated image was obtained from the WFPC2 Associations Science Products Pipeline. Apparent Vega magnitudes were determined from 1.5 σ isophotes using SExtractor (Bertin & Arnouts 1996). Galaxy sky orientation parameters, such as inclination angle (i) and azimuthal angle (Φ), were determined using GIM2D models (Simard et al. 2002) following the methods of Kacprzak et al. (2011). The image has a limiting magnitude of 25.5, which translates to a B -band absolute magnitude of $M_B = -15.2$ and $L = 0.004 L_*$ at $z = 0.43$.

The optical spectrum of the host galaxy was obtained using the Keck Echelle Spectrograph and Imager (ESI; Sheinis et al. 2002) on 2015 July 16 with an exposure time of 6000 s. The mean seeing was 0.9'' (FWHM) with variable cloud cover. The ESI slit is 20'' long and 1'' wide and we used 2×2 on-chip CCD binning. Binning by two in the spatial direction results in pixel sizes of 0.27'' – 0.34'' over the echelle orders of interest. Binning by two in the spectral direction results in a velocity dispersion of 22 km s^{−1} pixel^{−1} (FWHM ~ 90 km s^{−1}).

¹ Defined as $\frac{N_1}{N_0} = \frac{g_1}{g_0} \exp(-E_{01}/kT_{01})$, where N_i and g_i are the column density and statistical weight of the i th rotational level, respectively.

² <http://casa.colorado.edu/~danforth/science/cos/costools.html>

³ <http://www.astro.caltech.edu/~tb/makee/About.html>

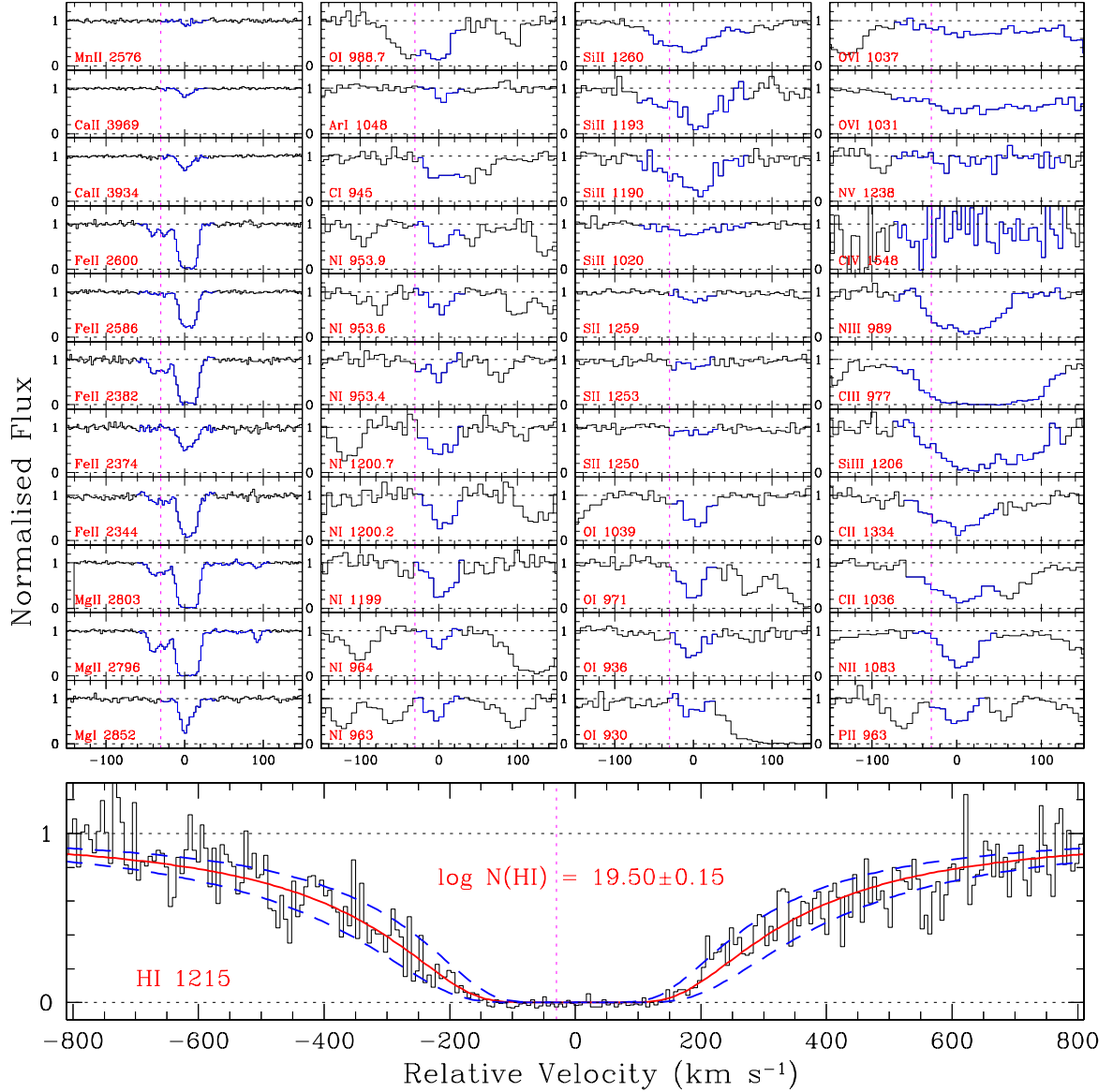


Figure 1. Velocity plot of the sub-DLA system studied here. The zero velocity corresponds to the redshift of the strongest metal-line component, i.e., $z_{\text{abs}} = 0.429805$. The vertical dotted line in each panel corresponds to the host galaxy redshift of $z_{\text{gal}} = 0.42966$. Bottom: Sub-damped Ly α profile of the absorber. The black histograms represent the data. The smooth (red) and dashed (blue) curves represent the best-fitting Voigt profile and its 1σ uncertainty, respectively. Top: Various metal lines arising from the same system. The absorption lines plotted in the leftmost panel are detected in the HIRES spectra. All other absorption lines are from COS spectra. The relevant part of each line is marked in blue in order to distinguish it from an unrelated absorption. Note that NV and CIV are not detected in this system.

The spectrum was reduced using the standard echelle package in IRAF⁴ along with standard calibrations and was vacuum and heliocentric velocity corrected. The data were not flux calibrated due to the variable conditions of the sky. We use our own fitting software FITTER (see Churchill et al. 2000), which computes best-fit Gaussian amplitudes, line centers, and widths to obtain emission-line redshifts and equivalent widths.

The galaxy rotation curve was extracted following the

⁴ IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation.

methods of Kacprzak et al. (2010) where we extract individual spectra by summing 3-pixel-wide apertures at 1-pixel spatial increments along the slit. Each spatial spectrum is then wavelength calibrated by extracting spectra of the arc line lamps at the same spatial pixels as the extracted galaxy spectra. The centroid of each emission line in each spectrum was determined with a Gaussian fit using FITTER.

3. ABSORPTION ANALYSIS

3.1. Description of the Absorber

In Figure 1 we display the absorption profiles of Ly α and different metal lines arising from the $z_{\text{abs}} = 0.4298$ absorber. The Ly α absorption clearly shows a damping wing. Strong,

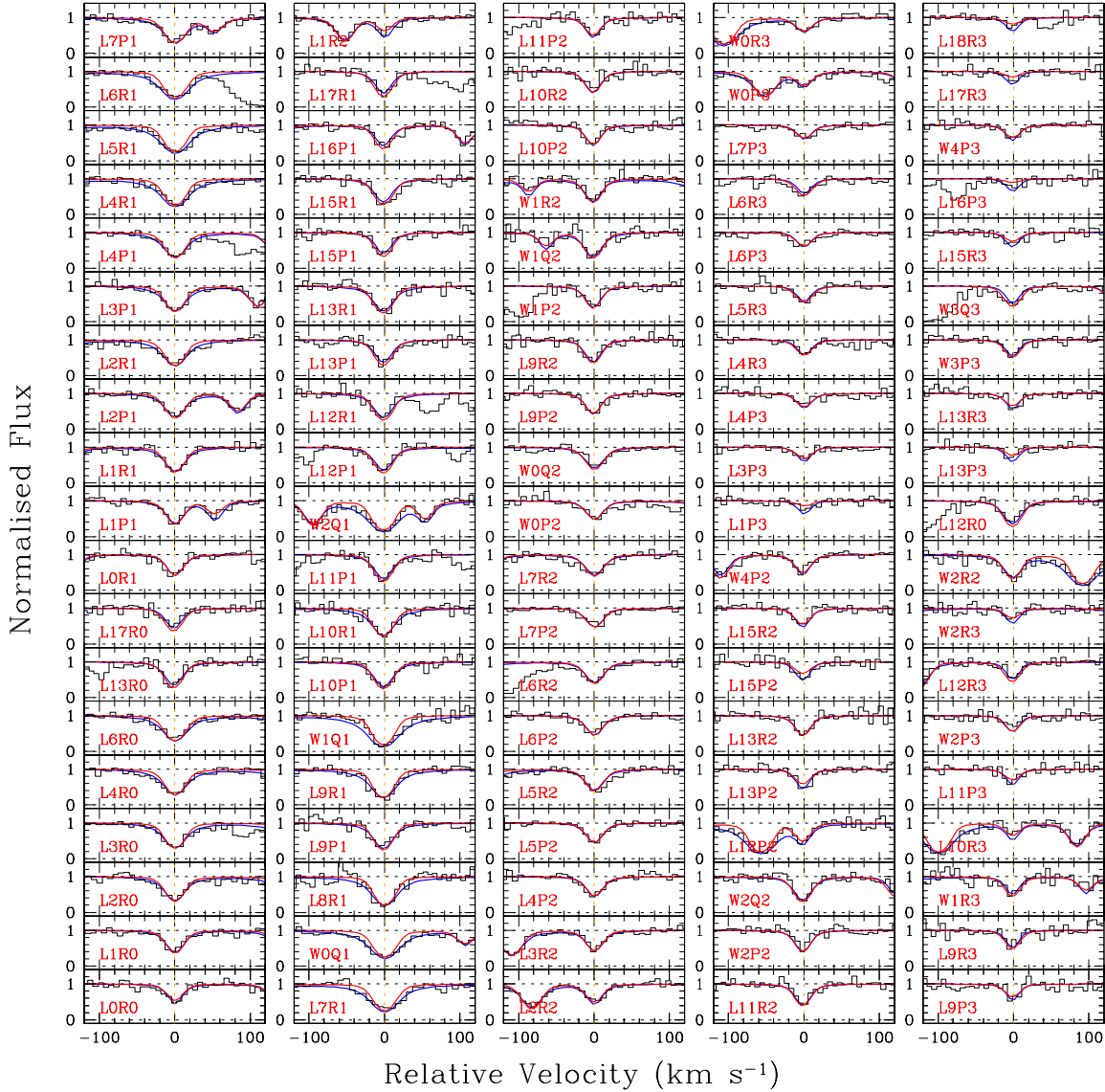


Figure 2. Velocity plot of numerous H_2 absorption lines from different J levels arising from the sub-DLA. The zero velocity corresponds to $z_{\text{abs}} = 0.429805$. The red and blue smooth curves are the best-fitting Voigt profiles to the data (black histograms) corresponding to the two different VPFIT solutions as discussed in the text. The blue curves correspond to a low b -parameter ($2.8 \pm 0.3 \text{ km s}^{-1}$) solution. The red curves represent a solution with $b(\text{H}_2) = 7.1 \pm 0.3 \text{ km s}^{-1}$. The low b -parameter solution results in an $N(\text{H}_2)$ of ~ 2 orders of magnitude higher as compared to the other. A b -parameter of 2.8 km s^{-1} is significantly lower than the spectral resolution of COS. Moreover, such a low b -value is not observed for the metal lines detected at the same velocity in the high-resolution Keck/HIRES data. We therefore prefer the solution with $b = 7.1 \text{ km s}^{-1}$, i.e., the red curves. Our photoionization model (see Section 3.3) further suggests that the $N(\text{H}_2)$ corresponding to the low b -parameter requires a density inconsistent with the observed $N(\text{Mg I})/N(\text{Mg II})$ ratio.

saturated absorption lines from $\text{Mg II } \lambda\lambda 2796, 2803$ doublets are detected in the high-resolution Keck spectrum. The very weak component at $v \sim +90 \text{ km s}^{-1}$ is not detected in any other neutral/singly ionized metal transitions. The two other weak components at $v \sim -40$ and -25 km s^{-1} are, however, present in the Mg I and Fe II absorption lines. The new COS observations cover several metal lines stemming from different elements (e.g., C, N, O, S, Si) and from different ionization states (e.g., O I, C III, O VI). Except for the C I⁵, all

other unblended neutral species (i.e., O I⁶, N I, and Ar I) exhibit a single-component, simple absorption kinematics. Except for the Si II $\lambda 1020$, P II $\lambda 963$, and N II $\lambda 1083$ ⁷, presence of multicomponent structure is seen in all other singly ionized and higher-ionization absorption lines⁸. Very strong, saturated C III absorption is detected over the entire velocity range

⁵ The red wing of the C I $\lambda 945$ line is partially blended, possibly with the Ly α absorption from the $z_{\text{abs}}=0.1118$ system.

⁶ The O I $\lambda 988.7$ line is self-blended with the weaker O I $\lambda 988.6$ and $\lambda 988.5$ lines.

⁷ We note that the N II line is partially blended with the Galactic C IV $\lambda 1550$ line.

⁸ Note that the red wing of the C II $\lambda 1036$ is contaminated with the L5R0 H_2 line detected from this sub-DLA. Moreover, the N III $\lambda 989$ line is partly blended with the Si II $\lambda 989.8$ absorption.

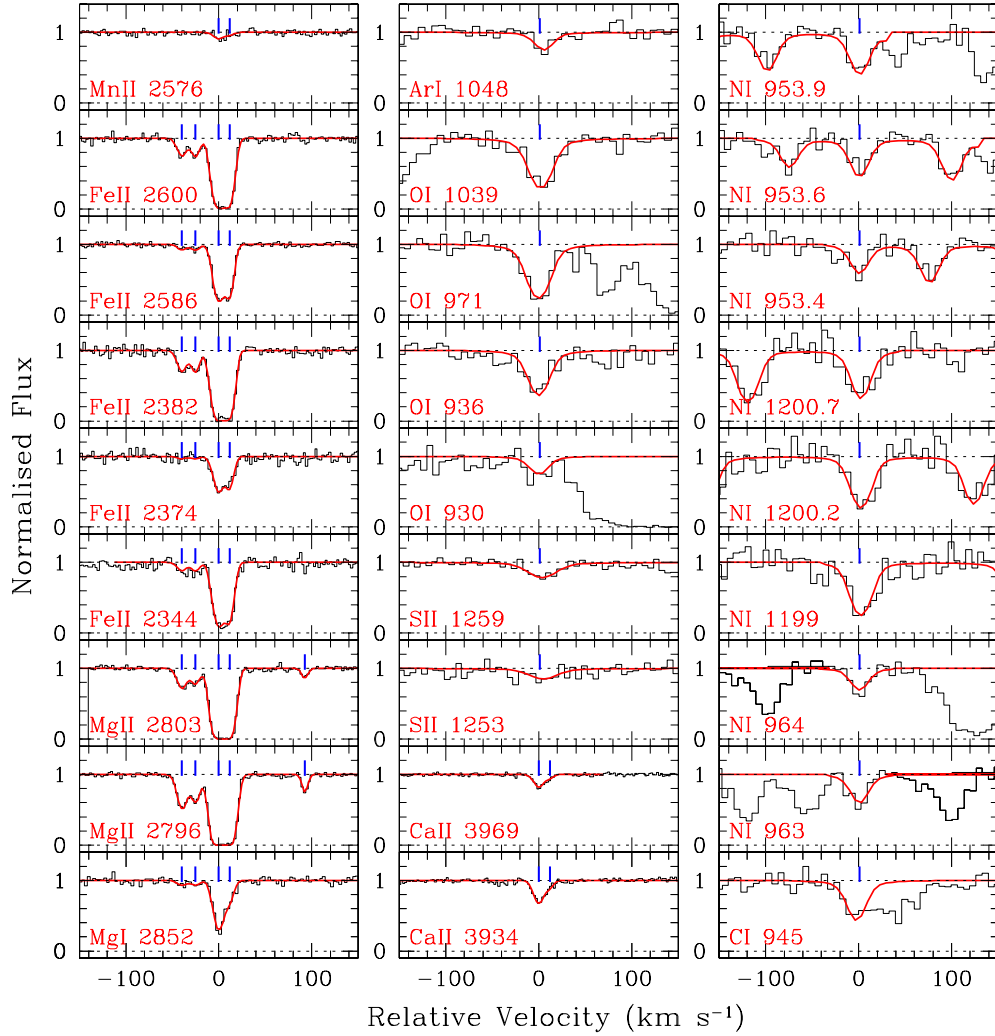


Figure 3. Voigt profile fits to the metal lines arising from the sub-DLA. The smooth red curves are the model profiles overplotted on top of data (black histograms). The zero velocity corresponds to $z_{\text{abs}} = 0.429805$. The line centroids of individual components used to fit a given line are marked by the blue ticks.

for which other low-ionization species, Mg II in particular, are detected.

The details of the high-ionization species are presented in Appendix A since the main focus of this paper is the low-ionization gas-phase giving rise to H₂ absorption. In brief, O VI $\lambda\lambda 1031, 1037$ absorption lines are detected in both the doublets in the velocity range of -100 to $+200$ km s⁻¹ with a total line spread of $\Delta v_{90} = 246$ km s⁻¹ (see Figure A1). No C IV and/or N V lines are detected in this system. The Voigt profile fit parameters for the O VI absorption and 3σ upper limits on $N(\text{N V})$ and $N(\text{C IV})$ are given in Table A1.

Besides several metal absorption lines, numerous Lyman- and Werner-band absorption lines of H₂, arising from the $J = 0, 1, 2$, and 3 rotational levels, are detected from this absorber. The H₂ absorption lines that are not self-blended or contaminated by other unrelated absorption are shown in Figure 2. Similar to neutral metal-line transitions detected in the COS spectra, the H₂ lines from different J levels also show a single-component, simple absorption kinematics. Importantly, the absorption redshifts of H₂ transitions coincide with the strongest metal-line component.

3.2. Absorption Line Measurements

We primarily use the vPFIT⁹ software for measuring absorption line parameters (i.e., N , b , and z). Additionally, whenever possible, we have used the curve-of-growth (COG) and the apparent optical depth (AOD) techniques. First, we fit all the metal lines detected in the high-resolution Keck spectrum simultaneously, i.e., by keeping the absorption redshift and b -parameter of a given component tied to each other. A minimum of five components are required to fit the Mg II doublets satisfactorily. As noted earlier, the weak component at $v \sim +90$ km s⁻¹ is not present in any other lines detected in the Keck spectrum. Except for the component at 0 km s⁻¹, we tied the b -parameter of different ions via thermal broadening with a gas temperature of 10^4 K. We note that a gas cloud photoionized by the extragalactic UV background radiation cannot cool efficiently below 10^4 K via metal-line cooling (Wiersma et al. 2009). Therefore, it is expected that the components without detected H₂ will have gas temperatures on the order of or higher than 10^4 K. For the strongest metal-

⁹ <http://www.ast.cam.ac.uk/~rfc/vpfit.html>

line component at 0 km s^{-1} , we set the temperature to be 156 K , i.e., the rotational excitation temperature (T_{01}) we obtain from the H_2 column densities in the $J = 0$ and $J = 1$ levels as discussed below. The Voigt profile fit parameters are summarized in Table 1, and the model profiles are shown in Figure 3. Since there is no $\text{Ly}\alpha$ forest crowding at low- z and the absorption lines of interest do not fall on top of any emission line, the continuum fitting uncertainty is generally small and is not taken into account in the absorption-line fit parameters.

Next, we fit the sub-DLA profile detected in the medium-resolution COS spectrum. Note that the line-spread function (LSF) of the COS is not a Gaussian. For our Voigt profile fit analysis we adopt the latest LSF given by Kriss (2011). The LSF was obtained by interpolating the LSF tables at the observed central wavelength for each absorption line and was convolved with the model Voigt profile while fitting absorption lines using VPFIT. The total H I column density we obtain by fitting the damping wing (Figure 1) of the $\text{Ly}\alpha$ absorption is $N(\text{H I}) = 10^{19.50 \pm 0.15} \text{ cm}^{-2}$.

Following Muzahid et al. (2015b), we choose a set of uncontaminated H_2 lines for Voigt profile fitting (see Figure 2). We fit them simultaneously by keeping the b -parameter tied. Additionally, we constrain the column density to be the same for all the transitions from a given J level and allow it to be different for different J levels. The COS wavelength calibration is known to have uncertainties at the level of $10\text{--}15 \text{ km s}^{-1}$ (Savage et al. 2011). We use the numerous H_2 absorption lines as guides to improve the wavelength calibration uncertainty. Our final corrected spectrum has a velocity accuracy of $\sim \pm 5 \text{ km s}^{-1}$. As a consequence, we did allow the redshift of individual transitions to be different from each other by a maximum of $\pm 5 \text{ km s}^{-1}$.

We noticed that, depending on the initial-guess b -parameter, VPFIT converges at two different solutions with significantly different total $N(\text{H}_2)$ values. The fit parameters are summarized in Table 2. For an initial-guess b -value of $\geq 8 \text{ km s}^{-1}$, VPFIT converges with a $b(\text{H}_2)$ of 7.1 ± 0.3 and a total $\log N(\text{H}_2) = 16.36 \pm 0.08$. On the other hand, an initial-guess b -value of $< 8 \text{ km s}^{-1}$ leads to a solution with a $b(\text{H}_2)$ of 2.8 ± 0.3 and a total $\log N(\text{H}_2) = 18.27 \pm 0.03$. Such a degeneracy is also present when we use the standard COG technique. The model profiles corresponding to the two different solutions are shown in Figure 2. From the model profiles and/or from the reduced χ^2 values, it is difficult to choose one model as opposed to the other. However, we note that the b -parameter in the latter case is significantly lower as compared to the velocity resolution of the COS spectra ($\sim 18 \text{ km s}^{-1}$). Such a narrow b -value is not measured in the corresponding metal-line component, even in the high-resolution Keck data. Furthermore, we demonstrate in the next section that the observed $N(\text{Mg I})$ to $N(\text{Mg II})$ ratio does not allow $N(\text{H}_2)$ to be as high as $10^{18.27} \text{ cm}^{-2}$. As such, we exclude the higher $N(\text{H}_2)$ solution.

The unblended lines of N I, O I, Ar I, and S II, detected in the COS spectra, are fitted with a single-component Voigt profile keeping both redshift and b -parameter free (see Table 3). The weak Ar I absorption is detected only in the $\lambda 1048$ transition¹⁰. A free fit to the Ar I $\lambda 1048$ leads to a highly erroneous solution. We, therefore, fix the b -parameter at 6.3 km s^{-1} , which we obtained from the fit to the strongest metal-line

Table 1
Component-by-component Voigt Profile Fit Parameters for the Metal Lines Detected in the High-resolution Keck Spectrum.

Ion	z_{abs}	$b \text{ (km s}^{-1}\text{)}$	$\log N/\text{cm}^{-2}$	$T(\text{K})^1$
Mg I	0.429616 ± 0.0000013	5.9 ± 0.4	10.82 ± 0.16	10^4
Mg II	...	5.9 ± 0.0	12.28 ± 0.02	...
Fe II	...	5.6 ± 0.0	12.34 ± 0.03	...
Mg I	0.429685 ± 0.0000015	5.0 ± 0.5	10.76 ± 0.17	10^4
Mg II	...	5.0 ± 0.0	12.10 ± 0.03	...
Fe II	...	4.6 ± 0.0	12.31 ± 0.03	...
Mg I	0.429805 ± 0.0000009	6.3 ± 0.2	12.08 ± 0.02	156^a
Mg II	...	6.3 ± 0.0	13.91 ± 0.04	...
Fe II	...	6.3 ± 0.0	13.68 ± 0.02	...
Ca II	...	6.3 ± 0.0	11.90 ± 0.02	...
Mn II	...	6.3 ± 0.0	11.72 ± 0.09	...
Mg I	0.429862 ± 0.0000011	4.4 ± 0.2	11.40 ± 0.06	10^4
Mg II	...	4.4 ± 0.0	13.73 ± 0.05	...
Fe II	...	4.0 ± 0.0	13.49 ± 0.02	...
Ca II	...	4.1 ± 0.0	11.22 ± 0.07	...
Mn II	...	4.0 ± 0.0	11.20 ± 0.26	...
Mg II	0.430245 ± 0.0000014	1.9 ± 0.8	11.75 ± 0.04	... ^b
Fe II	< 11.00	...
Mg I	< 10.60	...

Notes— ¹ Assumed gas temperature in the Voigt profile model. ^a Constrained from the T_{01} measured from the column densities of $J = 0$ and $J = 1$ levels of H_2 . ^b Not assumed since no ions other than Mg II are detected.

component detected in the Keck spectrum. The b -parameter of $16.8 \pm 4.0 \text{ km s}^{-1}$ required for a free fit to the weak S II absorption lines is higher than that is observed for the other lines. Nevertheless, the estimated column density is robust since the lines are weak and fall on the linear part of the COG. Finally, due to the blend in the red wing of the C I absorption, we estimate the maximum column density that can be accommodated by keeping the b -parameter and component velocity (i.e., z_{abs}) the same as the Mg I line. We treat the $N(\text{C I})$ obtained by this method as a conservative upper limit.

Next, we perform COG analysis for the ions detected in the medium-resolution COS spectra with at least three available unblended transitions. The results of our COG analyses are shown in Figure 4. The best-fitting COG column densities and b -parameters are given in each panel of the figure. The b -parameters obtained for both O I and N I, using the COG method, are consistent with the b -parameter we measure for the strongest absorption component in the Keck spectrum. Moreover, they are also consistent with the values we obtain using VPFIT within 1σ allowed uncertainties (see Table 3). The inferred b -parameter for Si II is somewhat higher than those for O I and N I. This is possibly due to the presence of multiple components in the strong Si II transitions. The b -parameter for S II is not well constrained since all three transitions are on the linear part of the COG. It is interesting to note that at least one line in each case falls on the linear part of the COG, ensuring that the column densities we obtain using COG are robust.

The AOD technique (Savage & Sembach 1991) is known to provide accurate column density measurements for unsaturated absorption lines. For saturated absorption the AOD method yields a lower limit on the column density. The column densities from AOD measurements are also listed in Table 4. Note that AOD column densities are consistent, within 1σ measurement uncertainties, with both VPFIT and COG column densities, whenever available. For our ionization mod-

¹⁰ The expected wavelength range for the other weaker transition of Ar I (i.e., $\lambda 1066$) is noisy and partly blended with the L3P2 line of H_2 .

Table 2
Voigt profile fit parameters of H₂.

z_{abs}	$b(\text{H}_2)$ (km s ⁻¹)	$\log N(\text{H}_2)$					$\log N(\text{H}_2)_{\text{tot}}$ (cm ⁻²)	$\log f_{\text{H}_2}$	T_{01} (K)	χ^2_{red}
		$J = 0$	$J = 1$	$J = 2$	$J = 3$	$J = 4$				
0.429807	7.1 \pm 0.3	15.74 \pm 0.08	16.22 \pm 0.09	15.23 \pm 0.03	14.83 \pm 0.03	<13.8	16.36 \pm 0.08	-2.84 \pm 0.17	156 \pm 47	2.1
0.429807	2.8 \pm 0.3	17.65 \pm 0.04	18.09 \pm 0.02	17.23 \pm 0.07	15.93 \pm 0.15	<13.5	18.27 \pm 0.03	-0.98 \pm 0.14	143 \pm 17	2.0

Notes– (1) Median absorption redshift. All H₂ absorption lines from different J levels are consistent within ± 5 km s⁻¹ of the median redshift. (2) Doppler parameters obtained from Voigt profile fitting. Note that VPFIT converges at two different solutions depending on the initial $b(\text{H}_2)$ values (see text). (3) H₂ column densities for different J levels. Standard 3σ upper limits, obtained from the nondetection of the L10R4 transition ($f\lambda = 30.76$), are provided for the $J = 4$ level. Limits are calculated assuming that the b -parameter of the undetected L10R4 line is the same as the corresponding $b(\text{H}_2)$ listed in column 2. (4) Total H₂ column density, i.e., the sum of column densities obtained from different J levels. (5) Logarithmic molecular fraction. (6) Rotational excitation temperature. (7) Reduced χ^2 value for the fit as returned by VPFIT.

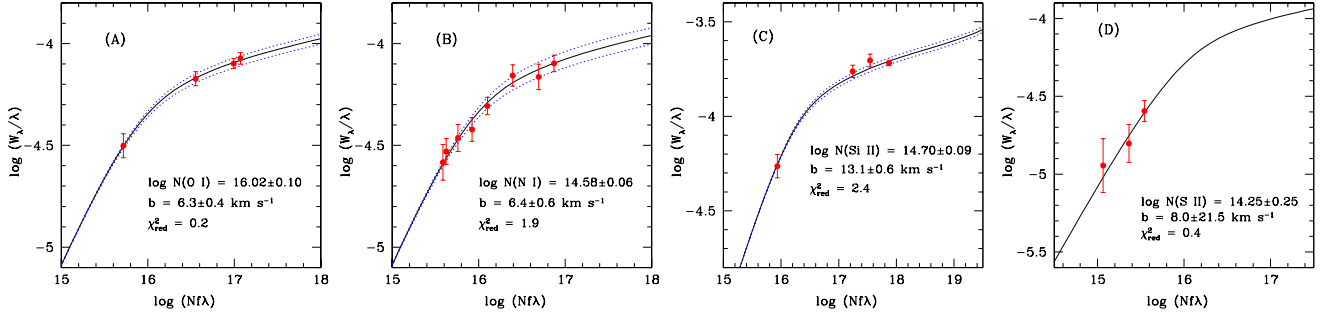


Figure 4. Results of COG analysis for O I, N I, Si II, and S II in panels A, B, C, and D, respectively. Note that for each case at least one transition is on the linear part of the COG, which enables us to estimate the total column density robustly. This is further supported by the independent AOD measurements of the weak lines (see Table 4) that are on the linear part of the COG.

Table 3

Single-component Voigt Profile Fit Parameters for the Metal Lines Detected in the Medium-resolution COS Spectra.

Ion	z_{abs}	b (km s ⁻¹)	$\log N/\text{cm}^{-2}$
N I	0.429815 \pm 0.000003	6.8 \pm 0.6	14.78 \pm 0.06
O I	0.429811 \pm 0.000003	7.7 \pm 0.3	15.87 \pm 0.06
Ar I	0.429828 \pm 0.000010	6.3 \pm 0.0	13.14 \pm 0.08
C I	0.429805 \pm 0.000000	6.3 \pm 0.0	13.88 \pm 0.13 ^a
S II	0.429818 \pm 0.000012	16.8 \pm 4.0	14.33 \pm 0.06

Notes– Zero error indicates that the corresponding parameter was kept tied/fixed while fitting. ^aThis value should be treated as an upper limit.

eling in the next section we adopt the column densities that are listed in the last column of Table 4. For a given ion, the adopted column density is simply the average of total column densities we obtained using the different methods (i.e. VPFIT, COG, and AOD).

3.3. Ionization Models

In this section we explore the chemical/physical conditions of the cool gas-phase, giving rise to a plethora of H₂ and neutral/singly ionized metal absorption lines, using the photoionization simulation code CLOUDY (v13.03, last described by Ferland et al. 2013). We use the observed total column densities of different species to constrain the model parameters and assume that all the $N(\text{H I})$ is associated with the H₂ component (but see Srianand et al. 2012). In order to obtain an accurate H₂ equilibrium abundance, we use full J resolved calculations, as described in Shaw et al. (2005), using the ‘ATOM H₂’ command. The ionizing radiation used in our model is the extragalactic UV background radiation at $z = 0.42$ contributed by both QSOs and galaxies (Haardt & Madau 2012). In addition, cosmic rays are added with an ion-

Table 4

Summary of total column density measurements.

Ion	VPFIT	AOD ^a	COG	Adopted Value ^b
O I	15.87 \pm 0.06	15.90 \pm 0.19	16.02 \pm 0.10	15.93 \pm 0.12
S II	14.33 \pm 0.06	14.21 \pm 0.20	14.25 \pm 0.25	14.26 \pm 0.16
Si II	...	14.61 \pm 0.30	14.70 \pm 0.09	14.66 \pm 0.18
C I	<13.9	<13.9
N I	14.78 \pm 0.06	14.55 \pm 0.19	14.58 \pm 0.06	14.65 \pm 0.09
Ar I	13.14 \pm 0.08	12.99 \pm 0.28	...	13.10 \pm 0.16
Mg I	12.20 \pm 0.04	12.20 \pm 0.14	...	12.20 \pm 0.09
Mg II	14.14 \pm 0.04	>13.7	...	14.14 \pm 0.04
Fe II	13.92 \pm 0.02	13.90 \pm 0.09	...	13.91 \pm 0.05
Mn II	11.83 \pm 0.13	11.93 \pm 0.64	...	11.88 \pm 0.41
Ca II	11.98 \pm 0.03	11.97 \pm 0.17	...	11.98 \pm 0.10

Notes– Measurement is not taken using the particular method when empty. ^aExcept for the S II and Fe II the weakest available transitions are used for estimating AOD column densities. The weakest transitions of S II ($\lambda 1250$ and $\lambda 1253$) and Fe II ($\lambda 2374$) are noisy and hence are not used. ^bAdopted column densities for our photoionization model.

ization rate of $\log \Gamma_{\text{CR}} = -17.3$ (Williams et al. 1998). We do not consider the effect of a galaxy/stellar radiation field since we do not know the SFR of the host galaxy. However, we note that the effect of a galaxy radiation field will be negligible at this redshift for an impact parameter of ~ 50 kpc from a sub- L_* ($\sim 0.5 L_*$) host galaxy (see, e.g. Narayanan et al. 2010; Werk et al. 2014). The lack of higher- J (i.e. $J > 3$) excitations also suggests that the prevailing radiation field is not strong (Shull & Beckwith 1982; Tumlinson et al. 2002). The absorbing gas is assumed to be a plane-parallel slab irradiated by the ionizing radiation from one side.

The total H I column density, i.e., $\log N(\text{H I}) = 19.50 \pm 0.15$, measured in this sub-DLA indicates that the absorbing gas is optically thick. Therefore, unlike the optically thin medium, the ionization corrections for different species

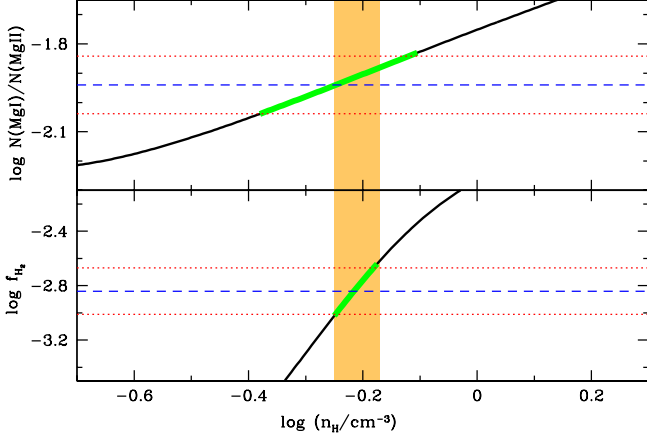


Figure 5. Photoionization-model-predicted molecular fraction (bottom) and Mg I-to-Mg II column density ratio (top) as a function of gas density. In each panel the horizontal dashed and dotted lines represent the corresponding observed value and its 1σ uncertainty, respectively. The vertical band indicates the allowed density range within which the model-predicted values of both $\log f_{\text{H}_2}$ and $\log N(\text{Mg I})/N(\text{Mg II})$ match with the observations. We adopt $\log n_{\text{H}} = -0.2$ as our density solution.

are no longer independent of the assumed metallicity and/or $N(\text{H I})$. Moreover, the dust-to-gas ratio is another important input model parameter since H_2 is present. The observed total $N(\text{O I})$ corresponds to an uncorrected gas-phase metallicity of $[\text{O}/\text{H}] = -0.26 \pm 0.19$. Thus, we use an input metallicity of $[\text{X}/\text{H}] = -0.3$ dex for our model. Assuming the intrinsic $[\text{Fe}/\text{X}]$ to be solar, the dust-to-gas ratio, relative to the solar neighborhood, is defined as

$$\kappa = 10^{[\text{X}/\text{H}]}(1 - 10^{[\text{Fe}/\text{X}]}) , \quad (1)$$

where X is an element that does not deplete onto dust significantly (see Wolfe et al. 2003). Assuming $\text{X} \equiv \text{S}$, we obtain $\log \kappa = -0.45$. Hence, we input $\log \kappa = -0.5$, with dust composition similar to Milky Way, in our model. The simulation is run on a density grid. For each density, the calculation is stopped when $N(\text{H I})$ in the simulation matches the observed value.

The variations of $\log f_{\text{H}_2}$ and the $N(\text{Mg I})/N(\text{Mg II})$ ratio with density in our model are shown in the bottom and top panels of Figure 5, respectively. Parameter f_{H_2} shows a sharp increase with density. The observed f_{H_2} value and its 1σ uncertainty correspond to a density in the range $\log n_{\text{H}} \simeq -0.15$ to -0.25 . Interestingly, the model-predicted $N(\text{Mg I})/N(\text{Mg II})$ ratios also match the observed value within 1σ allowed uncertainty in this density range. We therefore adopt $\log n_{\text{H}} = -0.2$, corresponding to an ionization parameter of $\log U = -5.6$, as the density solution. The predicted gas temperature at this density (i.e. 135 K) is also consistent with the observed T_{01} .

We use CLOUDY-computed ionization fractions of H I and different metal ions, at $\log n_{\text{H}} = -0.2$, for estimating ionization-corrected abundances. Abundances of different metals, after ionization corrections, are shown in Figure 6 and summarized in Table 5. Abundances are calculated using the standard convention: $[\text{X}/\text{H}] = \log(\text{X}/\text{H})_{\text{gas}} - \log(\text{X}/\text{H})_{\odot}$. Ionization correction, in this context, is defined as $\epsilon_{\text{X}} = \log(f_{\text{H I}}/f_{\text{X i}})$, where, $f_{\text{X i}}$ and $f_{\text{H I}}$ are the ionization fractions of the $(i - 1)$ th ionization state of element X and H I, respectively. It is apparent from Table 5, that with the ex-

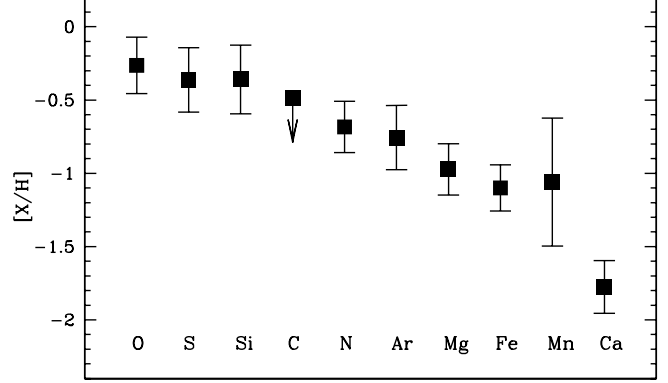


Figure 6. Ionization-corrected abundances of different elements for our adopted photoionization model. Note that the x -axis here does not represent anything. We find that Mg, Fe, Mn, and Ca are significantly depleted.

Table 5
Abundances of different elements.

Element	Ion	$[\text{X}/\text{H}]^a_{\text{uncorr}}$	ϵ_{X}^b	$[\text{X}/\text{H}]^c_{\text{corr}}$
O	O I	-0.26 ± 0.19	-0.003	-0.26 ± 0.19
S	S II	-0.36 ± 0.22	-0.002	-0.36 ± 0.22
Si	Si II	-0.35 ± 0.23	-0.009	-0.36 ± 0.23
C	C I	-2.03	$+1.542$	< -0.49
N	N I	-0.68 ± 0.17	-0.004	-0.68 ± 0.17
Ar	Ar I	$+0.04 \pm 0.22$	-0.800	-0.76 ± 0.22
Mg	Mg I	-2.90 ± 0.17	$+1.927$	-0.97 ± 0.17
Fe	Fe II	-1.09 ± 0.16	-0.010	-1.10 ± 0.16
Mn	Mn II	-1.05 ± 0.44	-0.009	-1.06 ± 0.44
Ca	Ca II	-1.86 ± 0.18	$+0.085$	-1.78 ± 0.18

Notes— ^a Abundance without ionization correction. ^b Ionization correction as defined in the text. ^c Abundance after ionization correction.

ception of O I and N I, the ionization correction is important (i.e., $|\epsilon_{\text{X}}| > 0.1$ dex) for all neutral species. On the other hand, except for Ca II, ionization corrections are negligibly small for all singly ionized species. The ionization-corrected abundance of oxygen $[\text{O}/\text{H}] = -0.26 \pm 0.19$ is the same as the uncorrected value. Sulfur and silicon have 0.1 dex lower abundances as compared to oxygen. Nevertheless, the abundances of O, S, and Si are consistent within 1σ . Estimated $[\text{C}/\text{O}] < -0.23$ and $[\text{N}/\text{O}] = -0.42 \pm 0.25$ suggest that both C and N are underabundant with respect to O. Additionally, we measure $[\text{Ar}/\text{H}] = -0.76 \pm 0.22$ dex. Similar abundance for the “inert gas” Ar is seen in the Milky Way “cool clouds” (Savage & Sembach 1996). A detailed discussion on elemental abundances and depletions is presented in Section 5.2.

Although the ionization model presented above is based on the observed total column densities, the dominating component is the one at $\sim 0 \text{ km s}^{-1}$ in which H_2 is present. This component comprises about $\sim 60\%$ of the total Mg II and Fe II, and $\sim 75\%$ of the total Mg I column densities. Thus, the model parameters essentially correspond to this component. Due to the lack of $N(\text{H I})$ information in individual components, we could not build component-by-component models. This is because all the higher-order Lyman series lines are heavily saturated. Nonetheless, from the measured $N(\text{Mg I})/N(\text{Mg II})$ and $N(\text{Mg II})/N(\text{Fe II})$ ratios we infer that the density in the two weak components at $v \sim -30 \text{ km s}^{-1}$ (see Figure 3) could be as high as seen in the H_2 component, provided that the metallicities are not very low. The weakest Mg II component at $v \sim 90 \text{ km s}^{-1}$ is more

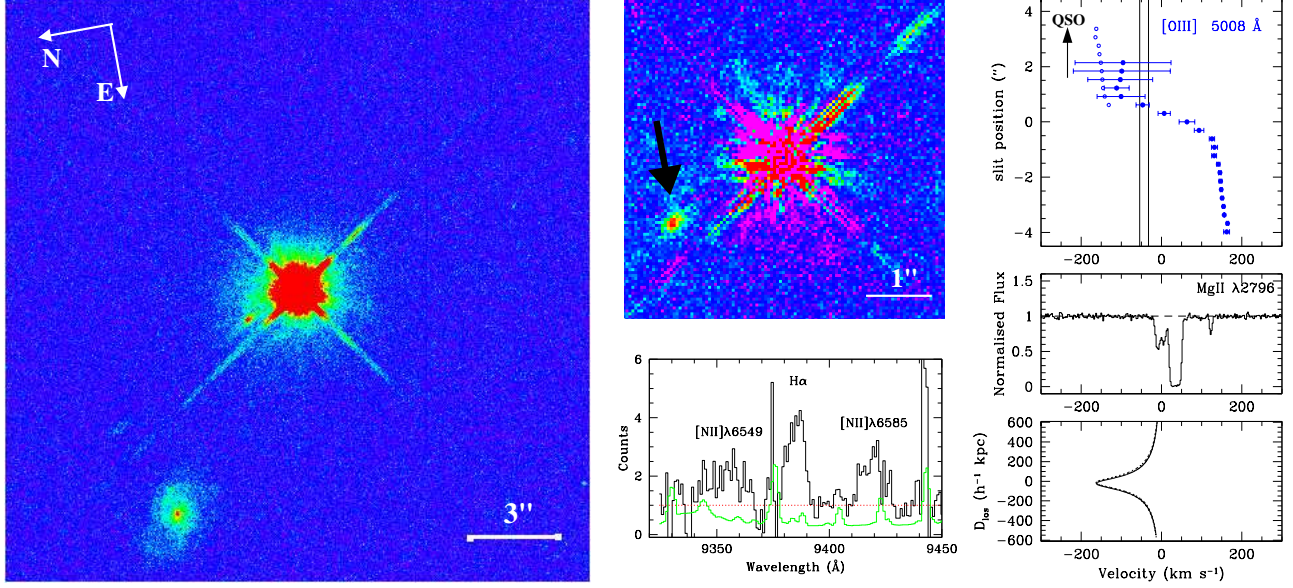


Figure 7. *Left:* *HST*/WFPC2 image of the QSO field. The host galaxy is located toward the northeast with respect to the QSO at the center. *Middle:* H α and N II emission lines from the host galaxy are shown in the bottom panel; the presence of another galaxy, possibly a dwarf-satellite of the host galaxy, is clearly visible in the QSO PSF-subtracted image of the field in the top panel. *Right:* The rotation curve, Mg II absorption kinematics, and the halo model of Steidel et al. (2002). The halo model is inconsistent with the Mg II kinematics for the most part (see text). The velocities below -50 km s^{-1} in the rotation curve are affected by a skyline contamination. The open circles in the rotation curve are the mirror of the corresponding measurements at $+ve$ velocities.

likely to be similar to the “weak systems” studied by Rigby et al. (2002).

If we use the higher $N(\text{H}_2)$ solution corresponding to $\log f_{\text{H}_2} = -0.98$ then the required density is $\log n_{\text{H}} = 0.8$, i.e., an order of magnitude higher than our adopted density. At such a high density the $N(\text{Mg I})/N(\text{Mg II})$ ratio is a factor of ~ 5 higher than the observed value. Additionally, the predicted photoionization equilibrium temperature at this density (i.e. 40 K) is significantly lower than the corresponding T_{01} value ($143 \pm 17 \text{ K}$; see Table 2). Next, Srianand et al. (2012) have found that H₂ components in high- z DLAs are compact (with sizes of $\lesssim 15 \text{ pc}$) and contain only a small fraction ($\lesssim 10\%$) of the total $N(\text{H I})$. If this is also true for the present system, then the H₂-bearing gas would require a much higher density ($> 10 \text{ cm}^{-3}$), which is inconsistent with the density range allowed by the $N(\text{Mg I})/N(\text{Mg II})$ ratio (see Figure 5). Finally, we note that an appreciable stellar contribution to the ionizing background on top of the extragalactic UV background would require a higher gas density in order to reproduce the same amount of $N(\text{H}_2)$ for a given $N(\text{H I})$ (see, e.g., Dutta et al. 2015; Muzahid et al. 2015b).

4. GALAXY ANALYSIS

The *HST*/WFPC2 F702W image of the field is shown in the left column of Figure 7. The host galaxy is located at an impact parameter of $\rho = 48.4 \text{ kpc}$ toward the northeast with respect to the QSO. The host galaxy has an inclination angle of $i = 48.3^{+3.5}_{-3.7} \text{ deg}$. The angle between the projected major axis of the host galaxy and the QSO sightline (i.e. the azimuthal angle, Φ) is $14.9^{+0.6}_{-4.9} \text{ deg}$. The azimuthal angle indicates that the absorbing gas is located near the projected major axis. The $B - K$ color of 2.06 (Nielsen et al. 2013), suggests a moderate star formation rate (SFR) in the host galaxy. Due to the unavailability of flux-calibrated spectra (see Section 2.2), we could not constrain the SFR of the host galaxy. Nonetheless, the presence of H α and

[N II] emission lines (see Figure 7), allowed us to measure a redshift of $z_{\text{gal}} = 0.42966 \pm 0.00016$ and a metallicity of $12 + \log(\text{O}/\text{H}) = 8.68 \pm 0.09$ for the host galaxy. The metallicity is estimated using the $N2$ relation of Pettini & Pagel (2004), i.e., $12 + \log(\text{O}/\text{H}) = 8.90 + 0.57 \times N2$, where $N2 \equiv \text{N II}/\text{H}\alpha$. We note that (i) the z_{gal} is consistent with the z_{abs} within 1σ uncertainty and (ii) the host galaxy has a metallicity consistent with the solar value (i.e., $12 + \log(\text{O}/\text{H}) = 8.69$, Asplund et al. 2009).

The point spread function (PSF) subtracted and magnified image of the QSO field is shown in the middle column of Figure 7. Interestingly, we found another galaxy at a much lower impact parameter ($\rho = 2.06''$) in this image. In fact, the presence of this dwarf galaxy is noticeable even in the left column of Figure 7. This galaxy could be a satellite of the bigger galaxy at $\rho = 48.4 \text{ kpc}$. However, we do not have a spectrum of this galaxy to constrain its redshift. Assuming that the dwarf galaxy is at z_{abs} , we obtain an impact parameter of $\rho = 11.6 \text{ kpc}$ and an apparent magnitude of $m_{\text{F702W}} = 23.20 \pm 0.06$ (Vega). The dwarf-satellite galaxy is highly inclined with $i = 70.0^{+15.0}_{-21.1} \text{ deg}$. Similar to the bigger galaxy, the projected major axis of the satellite galaxy also has a small azimuthal angle, i.e., $\Phi = 10.6^{+19.4}_{-10.6} \text{ deg}$, with respect to the QSO sightline.

The rotation curve of the spectroscopically confirmed host galaxy is constructed using the [O III] $\lambda 5008$ emission line and is shown in the right column of Figure 7. The zero velocity here corresponds to the z_{gal} and not to z_{abs} . The galaxy has a maximum projected rotation velocity of $|v_{\text{max}}| \sim 170 \text{ km s}^{-1}$. Note that the rotation curve at the $-ve$ velocities is affected by a skyline contamination to the [O III] $\lambda 5008$ line.

We now construct the halo model of Steidel et al. (2002) using i , Φ , ρ , and v_{max} of the host galaxy. Following Kacprzak et al. (2010) we use a gas scale height, h_v , a free parameter of the model, of 1000 kpc (for a non-lagging halo above the

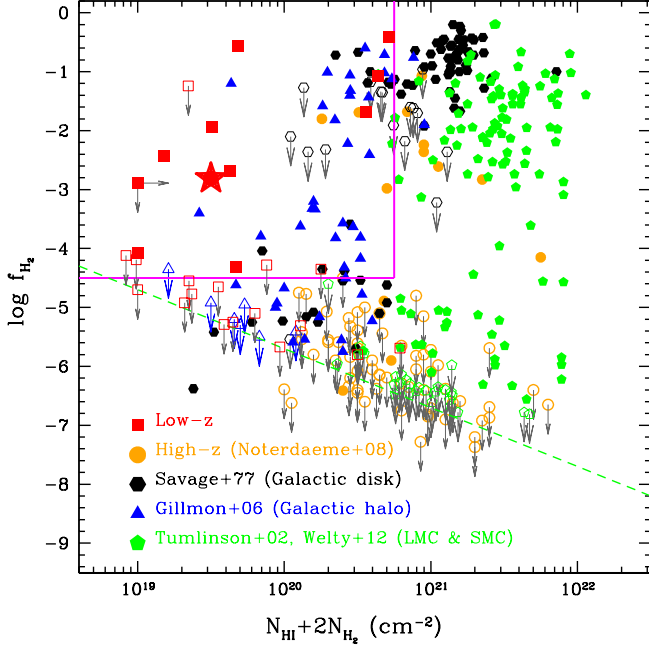


Figure 8. Molecular fraction versus the total hydrogen column density, $N(\text{HI} + \text{H}_2)$, for different astrophysical environments: low- z (Muzahid et al. 2015b) and high- z (Noterdaeme et al. 2008) DLAs/sub-DLAs, the Galactic disk (Savage et al. 1977) and halo (Gillmon et al. 2006), and the Magellanic Clouds (Tumlinson et al. 2002; Welty et al. 2012). For each sample, systems with detected H_2 are shown by filled symbols and the limits are shown by open symbols. The system studied here is shown by the red star. The magenta lines delineate the region ($\log f_{\text{H}_2} > -4.5$ and $\log N(\text{HI} + \text{H}_2) < 20.7$) within which all the low- z H_2 systems and a majority (i.e., $\sim 65\%$) of the Galactic halo systems reside. The dashed line corresponds to $\log N(\text{H}_2) = 14.0$, which can be treated as a typical detection threshold.

galaxy plane). Such a model examines the range of allowed velocities along the line of sight that are consistent with extended galaxy rotation. The model is shown in the bottom panel of the right column of Figure 7. The D_{los} is the distance along the line of sight relative to the point where the sight-line intercepts the projected mid-plane of the galaxy. A halo model is considered successful when the D_{los} curve spans the same velocity range as that of the observed Mg II absorption. It is important to notice that the observed Mg II kinematics is *not* consistent with such a model of a co-rotating disk but is consistent with a counter-rotating lagging halo.

5. DISCUSSION

5.1. Physical conditions

As mentioned in Section 1, the Lyman- and Werner-band absorption of H_2 is commonly observed in a wide variety of astrophysical environments. In Figure 8 we have summarized the H_2 observations from the literature. It is evident from the figure that the system studied here, consistent with other low- z H_2 systems, shows an unusually large f_{H_2} for its total (atomic+molecular) hydrogen column density, N_{H} . As noted by Muzahid et al. (2015b), the low- z H_2 systems populate the upper left corner of the f_{H_2} - N_{H} plane, as marked by the magenta lines in the plot. H_2 systems in the Galactic disk (Savage et al. 1977), Magellanic Clouds (Tumlinson et al. 2002; Welty et al. 2012), and high- z samples (Noterdaeme et al. 2008) are mostly DLAs with $\log N_{\text{H}} > 20.7$. Additionally, the systems with $\log N_{\text{H}} < 20.7$ either do not show H_2

absorption or have $\log f_{\text{H}_2} < -4.5$. In contrast, a significant fraction ($\sim 65\%$) of the Galactic halo systems (Gillmon et al. 2006), with detected H_2 , have f_{H_2} and $N(\text{H}_2)$ values in the ranges similar to those seen for the low- z systems. The physical conditions in the H_2 -absorbing gas, therefore, are more similar to those found for diffuse molecular clouds in the Galactic halo than to those for molecular clouds in the Galactic disk.

The relative level populations of H_2 provide a sensitive diagnostic of gas temperature (Tumlinson et al. 2002; Srianand et al. 2005). The excitation diagram for this system, shown in Figure 9, indicates that all the J -levels are consistent with a single excitation temperature of $T_{\text{ex}} = 206 \pm 6$ K. Note that the T_{ex} is consistent with the T_{01} within the 1σ allowed range. Such gas temperatures, along with the observed $N(\text{HI})$ and f_{H_2} values, are consistent with the diffuse atomic gas-phase of the Galactic ISM as characterized by Snow & McCall (2006).

When H_2 is sufficiently shelf-shielded and collisional processes dominate the $J = 0$ and 1 level populations, T_{01} represents the kinetic temperature of the gas (Roy et al. 2006; Snow & McCall 2006). Using HI 21 cm observations, Roy et al. (2006) have shown that the HI spin temperatures, T_s , are correlated with the T_{01} for systems with $\log N(\text{H}_2) \gtrsim 16.0$. Note that Kanekar & Chengalur (2003) observed but did not detect HI 21 cm absorption from this sub-DLA. From the nondetection, the authors placed a 3σ lower limit on the spin temperature of $T_s > 980$ K, assuming a covering factor of $f_c \sim 1$. Clearly, such a high temperature is not consistent with our T_{ex} or T_{01} measurements. The apparent mismatch between T_s and T_{ex} (or T_{01}) could be due to a significantly lower covering factor of the H_2 -bearing gas-phase. Dense and compact structures of H_2 -absorbing gas with small covering fraction are commonly observed (e.g., Srianand et al. 2012; Dutta et al. 2015) and are predicted in numerical simulations as well (e.g., Hirashita et al. 2003).

The populations of higher rotational levels (i.e., $J > 3$) are determined by UV pumping and formation pumping (Shull & Beckwith 1982; Tumlinson et al. 2002). This system, consistent with other low- z H_2 absorbers, do not show absorption from $J > 3$ levels. The lack of high- J excitations clearly indicates an absence of a local UV radiation field. The large impact parameter ($\rho \sim 50$ kpc) of the identified host galaxy is consistent with such an observation.

5.2. Elemental abundances and dust

Measurements of elemental abundances in DLAs and sub-DLAs provide essential clues on cosmic history of gas and dust in host galaxies. The main challenge in deriving abundance, particularly in metal-rich systems, is to disentangle the nucleosynthetic contributions from dust depletion effects. Assessment of intrinsic abundance, from gas-phase abundance, of an element becomes complicated when a fraction of that element depletes onto dust. A non-negligible amount of dust with a dust-to-gas ratio of $\log \kappa = -0.45$ is present in the sub-DLA studied here. Nevertheless, we could estimate gas-phase abundances of several α -elements (i.e., O, S, Si, Ar, Mg, and Ca) and Fe-peak elements (i.e., Fe and Mn), as shown in Figure 6.

In general, metallicity is derived from $[\text{O}/\text{H}]$ due to the charge transfer reaction between HI and OI. The inferred metallicity from our photoionization model is $[\text{O}/\text{H}] = -0.26 \pm 0.19$. Petitjean et al. (2006) noted a correlation between gas-phase metallicity and H_2 detection for high- z DLAs in which higher-metallicity DLAs tend to show H_2

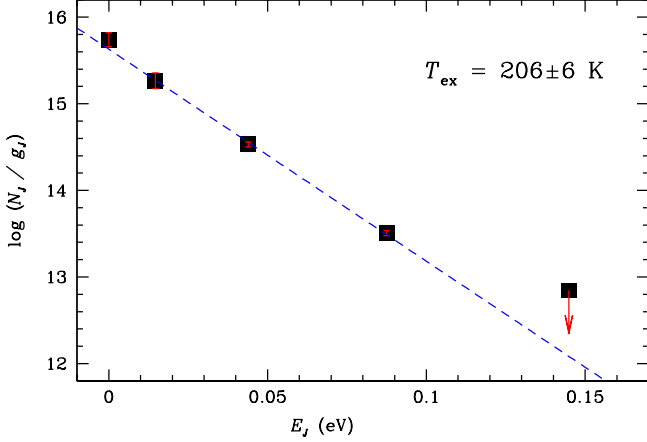


Figure 9. Excitation diagram for the rotational level populations of H₂. The population ratios of different rotational levels are expressed as a Boltzmann distribution [$N(J) \propto \exp(-E_J/kT)$]. Interestingly, a single excitation temperature can explain all the level populations.

more often than lower-metallicity systems (see also [Noterdaeme et al. 2008](#)). Furthermore, [Ledoux et al. \(2003\)](#) and [Noterdaeme et al. \(2008\)](#) found that the H₂ detection is more frequent for systems with higher $\log \kappa$ and $N_{\text{Fe}}^{\text{dust}}$ values, where the latter is the column density of dust in Fe. Note that all H₂ absorbers at high- z have $\log N_{\text{Fe}}^{\text{dust}} > 14.7$ and $\log \kappa > -1.5$. These observations are understood in view of efficient formation of H₂ on the surface of dust grains. Assuming the intrinsic [Fe/S] to be solar, a $\log \kappa$ of -0.45 corresponds to $N_{\text{Fe}}^{\text{dust}} \sim 10^{14.6} \text{ cm}^{-2}$ for the present system. Clearly, the detection of H₂ is consistent with the overall trends seen in high- z DLAs. Most importantly, the inferred high metallicity is inconsistent with a scenario of gas accretion since the accreting gas is typically metal poor with $[X/H] < -1.0$ ([Ribbaudo et al. 2011](#); [Kacprzak et al. 2012b](#); [Lehner et al. 2013](#)).

It is now well accepted that α -elements are produced via Type II supernovae (SNe II) from core collapse of massive ($> 8M_{\odot}$) stars. Fe-peak elements, on the contrary, arise in SNe Ia with low-/intermediate-mass progenitors. Delayed evolution of low- and intermediate-mass stars leads to a characteristic time gap of ~ 1 Gyr between formation of α -elements and Fe-peak elements (e.g., [Hamann & Ferland 1993](#)). Thus, the ratio of α -elements to Fe-peak elements with similar condensation temperatures, i.e., [Mg/Fe], provides a sensitive diagnostic of star formation history. We found $[\text{Mg}/\text{Fe}] = 0.13 \pm 0.23$, i.e. consistent with the solar value, for our system, indicating a lack of significant α -enhancement. Moreover, $[\text{Mg}/\text{Mn}] = 0.09 \pm 0.47$ is also consistent with the solar value. Therefore, it seems that Fe, Mg, and Mn all have similar gas-phase abundances of $[X/H] \sim -1.0$ indicating a moderate depletion of $\gtrsim 0.7$ dex. Similar depletion is seen in the Galactic “warm diffuse clouds” ([Savage & Sembach 1996](#)). Additionally, the heavy depletion of Ca as we observed here (i.e. > 1.5 dex) is also common in the Galactic diffuse ISM ([Welty et al. 1999](#)).

Oxygen is almost entirely produced by SNe II, primarily during the central H-burning phase. Carbon can be produced in stars of all masses via He burning. The synthesis of N can arise from primary and/or secondary production via the CNO cycle. If N is synthesized from C produced in the core of the same star via He burning, it is called primary. Sec-

ondary N enrichment of the ISM occurs well after massive stars have undergone SNe II and seeded the ISM with oxygen. For “primary N”, the [N/O] ratio is ~ -0.6 dex for $[\text{O}/\text{H}] < -0.3$. The [N/O] ratio increases with the [O/H] ratio for “secondary N” ([Pettini et al. 2008](#)). The observed $[\text{N}/\text{O}] = -0.42 \pm 0.25$ along with the near-solar metallicity suggest that the system lies near the “knee” of the [N/ α] versus $[\alpha/\text{H}]$ plot, and thus both primary and secondary channels could be responsible for the detected nitrogen (see Figure 9 of [Pettini et al. 2008](#)). Finally, the underabundance of C in our system (i.e., $[\text{C}/\text{O}] < -0.23$) is consistent with the measurements in Galactic halo stars (see [Akerman et al. 2004](#)).

5.3. Comparison with local analogs

First, we discuss the remarkable similarity in physical conditions between the present system and the H₂ absorber detected in HVC 287.5 + 22.5 + 240 probing the Leading Arm (LA) of the Magellanic Stream (see [Sembach et al. 2001](#)). The HVC is located at ~ 50 kpc from the Sun, similar to the impact parameter of the host galaxy of the $z_{\text{abs}} = 0.4298$ absorber. The HVC absorber shows $\log N(\text{H I}) = 19.90 \pm 0.05$, $\log N(\text{H}_2) = 16.80 \pm 0.10$, $\log f_{\text{H}_2} = -2.80 \pm 0.11$, and $T_{01} = 133^{+37}_{-21}$ K. All these values are surprisingly similar to the system studied here. Moreover, as in the present case, H₂ is detected only up to the $J = 3$ level. In fact, none of the extragalactic H₂ absorbers at low- z show high- J excitations (see Table 2 of [Muzahid et al. 2015b](#)). The abundance of sulfur ($[\text{S}/\text{H}] = -0.60$) and dust-to-gas ratio ($\log \kappa = -0.66$), as measured in the HVC, are somewhat lower as compared to the present system. Based on the similarity in abundance pattern between the absorber and warm gas in the SMC, the authors concluded that H₂ in the HVC is remnant material tidally stripped from the SMC. The large *in situ* H₂ formation time (~ 1 Gyr) derived for the system further suggested that tidal stripping is the most relevant origin.

Next, we discuss the H₂ absorbers in the IVCs, with $|v_{\text{LSR}}| = 30\text{--}90 \text{ km s}^{-1}$, studied by [Richter et al. \(2003\)](#). The authors found a large sky coverage ($\sim 35\%$) of IVCs with $N(\text{H I}) > 2 \times 10^{19} \text{ cm}^{-2}$ and noted the ubiquity of a diffuse H₂ component in the Galactic IVCs. For example, H₂ is detected in 14 out of 29 (i.e., $48 \pm 13\%$) IVC sightlines with spectra sensitive to detect H₂ down to $\log f_{\text{H}_2} \sim -3$. Note that the H₂ detection rate becomes $31 \pm 11\%$ for the low- z DLA/sub-DLA sample of [Muzahid et al. \(2015b\)](#) when we apply a similar $\log f_{\text{H}_2}$ cutoff. Thus, the H₂ detection rate in low- z DLAs/sub-DLAs is somewhat lower but consistent with the H₂ detection rate in IVCs within the 1σ Poisson error. Nevertheless, the molecular fractions of $\log f_{\text{H}_2} = -5.3$ to -3.3 (with a median value of -4.3) obtained for the H₂-detected IVCs are significantly lower than those found for the extragalactic low- z H₂ absorbers with a median $\log f_{\text{H}_2} = -1.93 \pm 0.63$ (see [Muzahid et al. 2015b](#)). This is possibly due to the fact that the IVCs studied in the sample of [Richter et al. \(2003\)](#) are located between 0.3–2.1 kpc from the plane of the Galactic disk. For the low- z H₂ absorbers, including the one studied here, the host galaxies are identified at $\rho > 10$ kpc. Thus, albeit having near-solar to solar metallicities, the IVCs show lower molecular fractions, perhaps due to the higher radiation field in closer proximity to the Galaxy.

5.4. Origin of sub-DLA and H₂

From the discussions above it is clear that the physical conditions and the chemical compositions of the H₂-bearing gas

are comparable to the diffuse atomic gas-phase (Snow & McCall 2006) which is consistent with the large impact parameter of the identified host galaxy. But how can molecules exist at ~ 50 kpc from the host galaxy? In Section 4 we have shown that the observed Mg II kinematics is inconsistent with a co-rotating, extended disk. In addition, from the B -band absolute magnitude ($M_B = -20.35$) of the host galaxy we obtain the effective radius of the H I disk of only ~ 13 kpc using the scaling relation of Lah et al. (2009). Thus, the absorber is not stemming from an extended H I disk.

Molecular gas in a galaxy halo could arise either from (i) *in situ* formation (Richter et al. 2003) or from (ii) ejected disk material via a central starburst (Geach et al. 2014) or through tidal/ram pressure stripping from a satellite galaxy (Sembach et al. 2001). H_2 formation takes place efficiently on the surface of dust grains if the gas is cool ($T \sim 100$ K), dense, and mostly neutral (Hollenbach & Salpeter 1971; Shull & Beckwith 1982). In such a case, the volume formation rate of H_2 can be expressed as Rn_H , where R is the formation rate coefficient. $R \sim (1 - 3) \times 10^{-17} \text{ cm}^3 \text{ s}^{-1}$ in the Galactic ISM (Jura 1974). For the range of physical conditions for the present system, the *in situ* H_2 formation time is $t_f \sim (Rn_H)^{-1} \sim 5 \times 10^9 \text{ yr}$ for $R = 10^{-17} \text{ cm}^3 \text{ s}^{-1}$ and $\log n_H = -0.2$. The large *in situ* formation time suggests that the idea of ejected disk material is more suitable.

Next, we discuss whether the absorbing gas is originating in an outflow from the host galaxy. Intervening absorption systems with high metallicities are generally thought to be tracing galactic-scale outflows (Tripp et al. 2011; Muzahid 2014; Muzahid et al. 2015a). Therefore, it is tempting to argue that the present system is probing a molecular outflow owing to its high gas-phase metallicity. Recent radio and millimeter observations have, indeed, detected large-scale molecular outflows (e.g., Alatalo et al. 2011; Geach et al. 2014). The molecular outflow studied by Alatalo et al. (2011) extends only up to ~ 100 pc and is thought to be powered by an active galactic nucleus. However, the other molecular outflow, studied by Geach et al. (2014), has a spatial extent up to ~ 10 kpc and is driven by stellar feedback from a compact starburst galaxy with an SFR of $260 M_\odot \text{ yr}^{-1}$. We note that the host galaxy of the present system is forming stars only at a moderate rate today. Besides, the azimuthal angle ($\sim 15^\circ$) suggests a large opening angle ($2\theta > 150^\circ$) for an outflow to intercept the QSO sightline. Note that an outflow from the dwarf-satellite candidate would require an opening angle of $2\theta > 160^\circ$.

Outflows from Seyfert galaxies typically have opening angles ranging between 60° – 135° (Hjelm & Lindblad 1996; Veilleux et al. 2001; Müller-Sánchez et al. 2011). In hydrodynamic simulations, the opening angles of outflows from star-forming galaxies are in the range $2\theta \simeq 10^\circ$ – 45° near the base and 45° – 100° above the disk (see Veilleux et al. 2005, and references therein). Outflow opening angles above the disk of $\sim 100^\circ$ are also confirmed via absorption-line studies (Kacprzak et al. 2012a, 2015; Bordoloi et al. 2014). As noted by Veilleux et al. (2005), the induced Kelvin-Helmholtz instabilities, as the wind propagates through the ISM, lead to fragmentation and subsequent mixing of the wind material. Thus, at a large distance (~ 50 kpc) it is *not* surprising to detect wind material even at small azimuthal angles unless the flow is highly collimated.

Finally, as mentioned in Section 4, there is a dwarf galaxy at a distance of ~ 12 kpc, provided that the galaxy has the same redshift as the absorber, from the QSO sightline. It is possible that the dwarf galaxy is interacting with the host

galaxy gravitationally. In such a case, materials from the outer disk of the satellite galaxy can get stripped off due to tidal forces or due to ram pressure. As discussed in the previous section, the detection of H_2 in the LA by Sembach et al. (2001) is an excellent analogy. The Magellanic Clouds are located at ~ 55 kpc from the MW, and the LA is thought to be stemming from tidal interaction between the Magellanic Clouds and the MW (see D’Onghia & Fox 2015, for a recent review). Future spectroscopic observations of the dwarf galaxy are essential for further understanding of this intriguing H_2 absorption system.

6. SUMMARY

We present a detailed analysis of an H_2 -detected sub-DLA at $z_{\text{abs}} = 0.4298$ in the spectra of QSO PKS 2128–123. Historically, the connection between a QSO absorber and an intervening galaxy was first demonstrated, observationally, by analyzing this absorber (i.e., Bergeron 1986). We revisit the absorber using preexisting data and new observations using *HST*/COS obtained under program ID 13398 as a part of our “Multiphase Gaseous Halos” survey. The absorber shows a plethora of absorption lines arising from neutral and ionized metals and molecular hydrogen. Below we briefly summarize our main results:

1. The total H I column density obtained by fitting the sub-DLA profile is $10^{19.50 \pm 0.15} \text{ cm}^{-2}$. The Lyman- and Werner-band absorption of H_2 is detected up to the $J = 3$ rotational level with a total $N(H_2) = 10^{16.36 \pm 0.08} \text{ cm}^{-2}$, corresponding to a molecular fraction of $\log f_{H_2} = -2.84 \pm 0.17$. The rotational excitation temperature of $T_{\text{ex}} = 206 \pm 6$ K, obtained from the H_2 level populations, reveals the presence of cold gas in the absorber. The measured $\log f_{H_2}$ and T_{ex} values are roughly consistent with the corresponding median values for the sample of low- z H_2 absorbers studied by Muzahid et al. (2015b).
2. Using a simple photoionization equilibrium model, we obtain a near-solar metallicity for the sub-DLA with oxygen abundance of $[O/H] = -0.26 \pm 0.19$ and a density of $\log n_H = -0.2$ (i.e., $0.6 \text{ particles cm}^{-3}$). Assuming the intrinsic $[Fe/S]$ to be solar, we measured a relative dust-to-gas ratio of $\log \kappa = -0.45$ and a column density of dust in Fe of $N_{\text{Fe}}^{\text{dust}} \sim 10^{14.6} \text{ cm}^{-2}$.
3. Ionization-corrected gas-phase abundances of nine different elements, besides oxygen, are calculated. The abundances of S and Si are consistent with O, suggesting a lack of depletion in these elements. The observed $[N/O] = -0.42 \pm 0.25$, along with $[O/H]$, makes this system lie near the “knee” of the $[N/\alpha]$ versus $[\alpha/H]$ plot (see, e.g., Pettini et al. 2008). The fact possibly implies that the synthesis of N in this absorber is contributed by both “primary” and “secondary” processes.
4. Both Fe and Mg show similar gas-phase abundances (i.e. $[X/H] \sim -1.0$) with $[Mg/Fe] = 0.13 \pm 0.23$ indicating a lack of (or no) significant α -enhancement. Additionally, we observe Mn and Fe having identical abundances. Therefore, Fe, Mg, and Mn seem to show a moderate ($\gtrsim 0.7$ dex) depletion. Ca, with $[Ca/H] = -1.78 \pm 0.18$, is, however, heavily depleted.

5. The host galaxy of the sub-DLA is detected at an impact parameter of ~ 48 kpc. The host galaxy has a B -band absolute magnitude of $M_B = -20.35$ (corresponding to $\sim 0.5 L_*$) and a $B - K$ color of 2.06 suggesting a moderate SFR (Nielsen et al. 2013). It has an inclination angle of $i \sim 48^\circ$ on the plane of the sky. The QSO sightline is at an azimuthal angle of $\sim 15^\circ$ from the projected major axis of the host galaxy.
6. Using models of Steidel et al. (2002) we found that the Mg II absorption kinematics cannot be explained by gas co-rotating with an extended disk. The effective radius of the H I disk of ~ 13 kpc, derived from M_B using the observed scaling relation of Lah et al. (2009), further refutes the origin of the absorber in an extended disk. Moreover, the high gas-phase metallicity of the absorber suggests that it is not tracing accreting materials. On the other hand, a large opening angle ($2\theta > 150^\circ$) is required for an outflow from the central region of the host galaxy to intercept the QSO sightline at an azimuthal angle of $\sim 15^\circ$.
7. We favor a scenario in which the absorber originates in a satellite dwarf galaxy. A large *in situ* H₂ formation timescale ($\sim 5 \times 10^9$ yr) indicates that the molecular gas, instead, is stemming from stripped-off disk material of the satellite galaxy due to (i) ram pressure, as the satellite moves into the dark matter potential of the bigger galaxy and/or (ii) tidal interaction between the satellite and the host galaxy. Interestingly, a dwarf galaxy is detected in the QSO PSF-subtracted *HST* image of the field at an impact parameter of ~ 12 kpc. Spectroscopic observations of the dwarf galaxy candidate are crucial for further comprehension on the origin of the sub-DLA.

This exercise emphasizes the importance of detailed analysis of QSO absorbers on a case-by-case basis. While studies of large samples provide useful information on overall properties of the absorbers, they often tend to oversimplify the inherent intricacies of the problem, in particular, the origin(s) of the absorbers. We seek to perform similar analysis for all the low- z H₂ absorbers (Muzahid et al. 2015b) in the future with new observations using *HST* and ground-based telescopes.

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Facilities: *HST*(COS, WFPC2), Keck(HIRES, ESI)

REFERENCES

- Akerman, C. J., Carigi, L., Nissen, P. E., Pettini, M., & Asplund, M. 2004, *A&A*, 414, 931
- Alatalo, K., Blitz, L., Young, L. M., et al. 2011, *ApJ*, 735, 88
- Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, *ARA&A*, 47, 481
- Bergeron, J. 1986, *A&A*, 155, L8
- Bertin, E., & Arnouts, S. 1996, *A&AS*, 117, 393
- Black, J. H., Chaffee, F. H., & Foltz, C. B. 1987, *ApJ*, 317, 442
- Bordoloi, R., Lilly, S. J., Kacprzak, G. G., & Churchill, C. W. 2014, *ApJ*, 784, 108
- Bouwens, R. J., Illingworth, G. D., Oesch, P. A., et al. 2011, *ApJ*, 737, 90
- Chen, H.-W., Kennicutt, Jr., R. C., & Rauch, M. 2005, *ApJ*, 620, 703
- Churchill, C. W., Mellon, R. R., Charlton, J. C., et al. 2000, *ApJS*, 130, 91
- Crighton, N. H. M., Bechtold, J., Carswell, R. F., et al. 2013, *MNRAS*, 433, 178
- Danforth, C. W., Stocke, J. T., & Shull, J. M. 2010, *ApJ*, 710, 613
- D’Onghia, E., & Fox, A. J. 2015, *ArXiv e-prints*, arXiv:1511.05853
- Dutta, R., Srianand, R., Muzahid, S., et al. 2015, *MNRAS*, 448, 3718
- Ferland, G. J., Porter, R. L., van Hoof, P. A. M., et al. 2013, *Rev. Mexicana Astron. Astrofis.*, 49, 137
- Geach, J. E., Hickox, R. C., Diamond-Stanic, A. M., et al. 2014, *Nature*, 516, 68
- Gillmon, K., Shull, J. M., Tumlinson, J., & Danforth, C. 2006, *ApJ*, 636, 891
- Gnat, O., & Sternberg, A. 2007, *ApJS*, 168, 213
- Green, J. C., Froning, C. S., Osterman, S., et al. 2012, *ApJ*, 744, 60
- Gringel, W., Barnstedt, J., de Boer, K. S., et al. 2000, *A&A*, 358, L37
- Haardt, F., & Madau, P. 2012, *ApJ*, 746, 125
- Hamann, F., & Ferland, G. 1993, *ApJ*, 418, 11
- Hirashita, H., Ferrara, A., Wada, K., & Richter, P. 2003, *MNRAS*, 341, L18
- Hjelm, M., & Lindblad, P. O. 1996, *A&A*, 305, 727
- Hollenbach, D., & Salpeter, E. E. 1971, *ApJ*, 163, 155
- Jura, M. 1974, *ApJ*, 191, 375
- Kacprzak, G. G., Churchill, C. W., Ceverino, D., et al. 2010, *ApJ*, 711, 533
- Kacprzak, G. G., Churchill, C. W., Evans, J. L., Murphy, M. T., & Steidel, C. C. 2011, *MNRAS*, 416, 3118
- Kacprzak, G. G., Churchill, C. W., & Nielsen, N. M. 2012a, *ApJ*, 760, L7
- Kacprzak, G. G., Churchill, C. W., Steidel, C. C., Spitler, L. R., & Holtzman, J. A. 2012b, *MNRAS*, 427, 3029
- Kacprzak, G. G., Muzahid, S., Churchill, C. W., Nielsen, N. M., & Charlton, J. C. 2015, *ApJ*, 815, 22
- Kanekar, N., & Chengalur, J. N. 2003, *A&A*, 399, 857
- Kriss, G. A. 2011, *Improved Medium Resolution Line Spread Functions for COS FUV Spectra*, Tech. rep.
- Lah, P., Pracy, M. B., Chengalur, J. N., et al. 2009, *MNRAS*, 399, 1447
- Ledoux, C., Petitjean, P., & Srianand, R. 2003, *MNRAS*, 346, 209
- Lehner, N. 2002, *ApJ*, 578, 126
- Lehner, N., Howk, J. C., Tripp, T. M., et al. 2013, *ApJ*, 770, 138
- Müller-Sánchez, F., Prieto, M. A., Hicks, E. K. S., et al. 2011, *ApJ*, 739, 69
- Muzahid, S. 2014, *ApJ*, 784, 5
- Muzahid, S., Kacprzak, G. G., Churchill, C. W., et al. 2015a, *ApJ*, 811, 132
- Muzahid, S., Srianand, R., & Charlton, J. 2015b, *MNRAS*, 448, 2840
- Narayanan, A., Savage, B. D., & Wakker, B. P. 2010, *ApJ*, 712, 1443
- Nielsen, N. M., Churchill, C. W., Kacprzak, G. G., & Murphy, M. T. 2013, *ApJ*, 776, 114
- Noterdaeme, P., Ledoux, C., Petitjean, P., & Srianand, R. 2008, *A&A*, 481, 327
- Oliveira, C. M., Sembach, K. R., Tumlinson, J., O’Meara, J., & Thom, C. 2014, *ApJ*, 783, 22
- Osterman, S., Green, J., Froning, C., et al. 2011, *Ap&SS*, 335, 257
- Petitjean, P., Ledoux, C., Noterdaeme, P., & Srianand, R. 2006, *A&A*, 456, L9
- Petitjean, P., Riediger, R., & Rauch, M. 1996, *A&A*, 307, 417
- Pettini, M., & Pagel, B. E. J. 2004, *MNRAS*, 348, L59
- Pettini, M., Zych, B. J., Steidel, C. C., & Chaffee, F. H. 2008, *MNRAS*, 385, 2011
- Rafelski, M., Wolfe, A. M., Prochaska, J. X., Neeleman, M., & Mendez, A. J. 2012, *ApJ*, 755, 89
- Ribaud, J., Lehner, N., Howk, J. C., et al. 2011, *ApJ*, 743, 207
- Richter, P., de Boer, K. S., Widmann, H., et al. 1999, *Nature*, 402, 386
- Richter, P., Sembach, K. R., Wakker, B. P., & Savage, B. D. 2001, *ApJ*, 562, L181
- Richter, P., Wakker, B. P., Savage, B. D., & Sembach, K. R. 2003, *ApJ*, 586, 230
- Rigby, J. R., Charlton, J. C., & Churchill, C. W. 2002, *ApJ*, 565, 743
- Roy, N., Chengalur, J. N., & Srianand, R. 2006, *MNRAS*, 365, L1
- Savage, B. D., Bohlin, R. C., Drake, J. F., & Budich, W. 1977, *ApJ*, 216, 291
- Savage, B. D., Lehner, N., & Narayanan, A. 2011, *ApJ*, 743, 180
- Savage, B. D., & Sembach, K. R. 1991, *ApJ*, 379, 245
- , 1996, *ARA&A*, 34, 279
- Sembach, K. R., Howk, J. C., Savage, B. D., & Shull, J. M. 2001, *AJ*, 121, 992
- Shaw, G., Ferland, G. J., Abel, N. P., Stancil, P. C., & van Hoof, P. A. M. 2005, *ApJ*, 624, 794
- Sheinis, A. I., Bolte, M., Epps, H. W., et al. 2002, *PASP*, 114, 851
- Shull, J. M., & Beckwith, S. 1982, *ARA&A*, 20, 163
- Simard, L., Willmer, C. N. A., Vogt, N. P., et al. 2002, *ApJS*, 142, 1

Snow, T. P., & McCall, B. J. 2006, ARA&A, 44, 367
 Som, D., Kulkarni, V. P., Meiring, J., et al. 2013, MNRAS, 435, 1469
 Spitzer, Jr., L., & Jenkins, E. B. 1975, ARA&A, 13, 133
 Srianand, R., Gupta, N., Petitjean, P., et al. 2012, MNRAS, 421, 651
 Srianand, R., Noterdaeme, P., Ledoux, C., & Petitjean, P. 2008, A&A, 482, L39
 Srianand, R., Petitjean, P., Ledoux, C., Ferland, G., & Shaw, G. 2005, MNRAS, 362, 549
 Srianand, R., Rahmani, H., Muzahid, S., & Mohan, V. 2014, MNRAS, 443, 3318
 Steidel, C. C., Kollmeier, J. A., Shapley, A. E., et al. 2002, ApJ, 570, 526
 Tripp, T. M., Meiring, J. D., Prochaska, J. X., et al. 2011, Science, 334, 952

Tumlinson, J., Shull, J. M., Rachford, B. L., et al. 2002, ApJ, 566, 857
 Veilleux, S., Cecil, G., & Bland-Hawthorn, J. 2005, ARA&A, 43, 769
 Veilleux, S., Shopbell, P. L., & Miller, S. T. 2001, AJ, 121, 198
 Wakker, B. P. 2006, ApJS, 163, 282
 Welty, D. E., Hobbs, L. M., Lauroesch, J. T., et al. 1999, ApJS, 124, 465
 Welty, D. E., Xue, R., & Wong, T. 2012, ApJ, 745, 173
 Werk, J. K., Prochaska, J. X., Tumlinson, J., et al. 2014, ApJ, 792, 8
 Wiersma, R. P. C., Schaye, J., & Smith, B. D. 2009, MNRAS, 393, 99
 Williams, J. P., Bergin, E. A., Caselli, P., Myers, P. C., & Plume, R. 1998, ApJ, 503, 689
 Wolfe, A. M., Prochaska, J. X., & Gawiser, E. 2003, ApJ, 593, 215

APPENDIX

A. ANALYSIS OF THE O VI ABSORPTION

In this appendix we discuss the properties of the high-ionization gas-phase traced by the O VI doublet. The Voigt profile decomposition of the detected O VI is shown in Figure A1. A minimum of three components are required for fitting both the doublet members adequately. Note that the O VI $\lambda 1037$ is blended with the L5P1 transition of H₂. The doublets are fitted simultaneously, taking into account the contribution of the H₂ line. The fit parameters are summarized in Table A1. As mentioned previously, C IV and N V are not detected in this system. Formal 3σ upper limits on column densities for these ions are also presented in the table.

We run constant-density CLOUDY simulations under optically thin conditions with a stopping $N(\text{H I})$ of 10^{14} cm^{-2} and the extragalactic UV background radiation at $z = 0.42$ (Haardt & Madau 2012) as the ionizing continuum. In Figure A2 we show the results of our photoionization model. In the top left corner of the figure the variations of $N(\text{O VI})/N(\text{C IV})$ and $N(\text{O VI})/N(\text{N V})$ ratios with density are shown. The observed lower limits on these ratios suggest $\log n_{\text{H}} < -4.4$, provided that the relative abundances of N, C, and O are solar. Underabundance of C or N with respect to O would require even lower densities. From the bottom left panel it is evident that the O VI ionization fraction, $f_{\text{O VI}}$, peaks at $\log n_{\text{H}} \simeq -4.5$ and decreases for $\log n_{\text{H}} > -5.0$. The O VI column density can be expressed as $N(\text{O VI}) = f_{\text{O VI}} 10^{[\text{O/H}]} (\text{O/H})_{\odot} n_{\text{H}} L_{\text{los}}$, where L_{los} is the line-of-sight thickness of the absorbing gas. Using the maximum $f_{\text{O VI}}$ value, i.e. at $n_{\text{H}} = -4.5$, it is now possible to examine how L_{los} changes with metallicity, $[\text{O/H}]$, of the absorber for a given $N(\text{O VI})$. The corresponding plot, for the strongest O VI component with $\log N(\text{O VI}) = 14.34$, is shown in the right panel of Figure A2. It is clear that a metallicity much lower than $1/10$ of solar (i.e. $[\text{O/H}] = -1.0$) is not permitted as it requires unreasonably large ($> 1 \text{ Mpc}$) line-of-sight thickness. If the high-ionization gas-phase has a metallicity similar to the H₂-bearing gas-phase (i.e. $[\text{O/H}] = -0.26$) then the deduced L_{los} is 28 kpc. Lower $f_{\text{O VI}}$ values at lower densities, since higher densities are forbidden, would require slightly higher values of L_{los} . But the thickness could be smaller for higher metallicities. Therefore, the detected O VI can have a reasonable solution under photoionization equilibrium provided that $[\text{O/H}] > -1.0$. The only caveat here is that we assumed that the $f_{\text{O VI}}$ is independent of metallicity, which is not strictly true for very high metallicities (e.g. $[\text{O/H}] > 0.5$). Nonetheless, the effect is small, and the cloud size becomes unreasonably large only at lower metallicities.

Finally, we note that if the O VI is in collisional ionization equilibrium (Gnat & Sternberg 2007), then the lower limits on the $N(\text{O VI})/N(\text{C IV})$ and $N(\text{O VI})/N(\text{N V})$ ratios require a gas temperature of $\log T > 5.4$, which is consistent with the maximum allowed temperatures evaluated from $b(\text{O VI})$ in Table A1. Thus, the high-ions can arise either from photoionization or from collisional ionization.

Table A1
Voigt profile fit parameters for the O VI absorption.

Ion	z_{abs}	$b \text{ (km s}^{-1}\text{)}$	$\log (N/\text{cm}^{-2})$	$\log (T_{\text{max}}/K)^1$
O VI	0.429872 ± 0.000018	53 ± 7	14.34 ± 0.04	6.54
N V			< 13.6	
C IV			< 13.8	
O VI	0.430227 ± 0.000019	15 ± 8	13.65 ± 0.17	5.71
N V			< 13.4	
C IV			< 13.5	
O VI	0.430561 ± 0.000026	47 ± 9	14.08 ± 0.06	6.48
N V			< 13.5	
C IV			< 13.6	

Note—¹Maximum logarithmic gas temperature calculated from $b(\text{O VI})$ and the corresponding error.

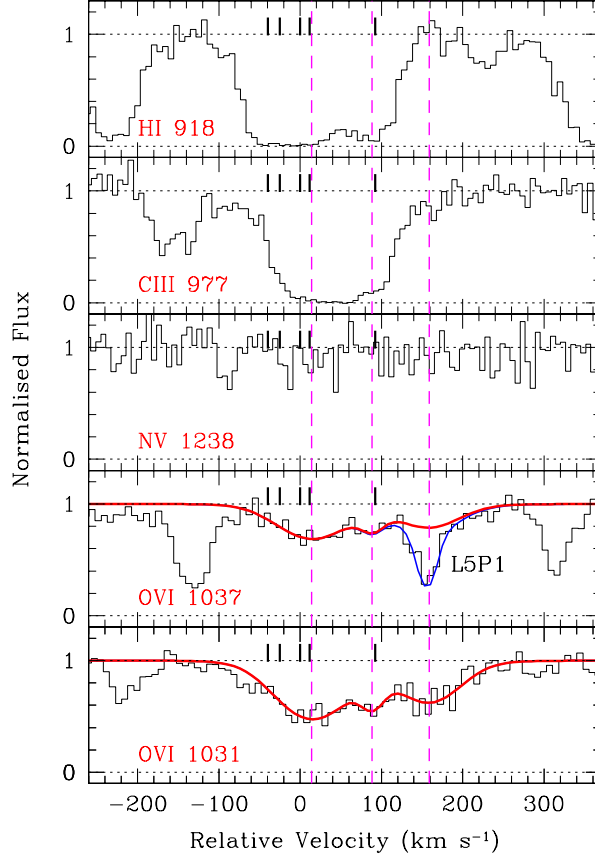


Figure A1. Voigt profile decomposition for the O VI absorption. The absorption profiles are plotted in velocity with respect to $z_{\text{abs}} = 0.429805$. The smooth red curves are the best-fitting Voigt profiles over-plotted on top of data (black histogram). The line centroids of O VI components are marked by vertical dotted lines. The solid black ticks represent the centroids of Mg II components. The O VI $\lambda 1037$ profile is blended with one of the H₂ transitions from the $J = 1$ level. H I $\lambda 918$ and C III absorption profiles are shown just for references.

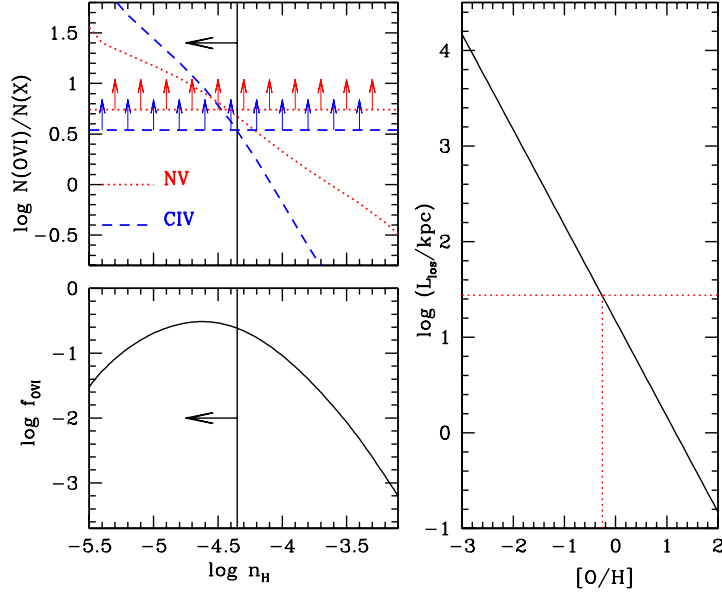


Figure A2. Photoionization model for the O VI. Top left: column density ratios against the absorber's density. The vertical line followed by an arrow indicates the allowed density range. Bottom left: ionization fraction, f_{OVI} , against the density. The f_{OVI} gradually increases with decreasing density to its peak at $\log n_{\text{H}} \simeq -4.5$ and then decreases again. Right: variation of line-of-sight thickness with absorber's metallicity for a gas cloud with $\log N(\text{OVI}) = 14.34$, $\log n_{\text{H}} = -4.5$ and $\log f_{\text{OVI}} = -0.50$ (the peak value). The dotted horizontal line represents L_{los} of 28 kpc corresponding to $[\text{O}/\text{H}] = -0.26$.